
Optical Observations of Isolated Neutron Stars

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Outline

- Motivation: Why Look in the Optical?
- Sample
- Specific Sources
 - RX J0720.4–3125
 - RX J1856.5–3754
- Conclusions

Motivation

INS are X-ray bright, optically faint

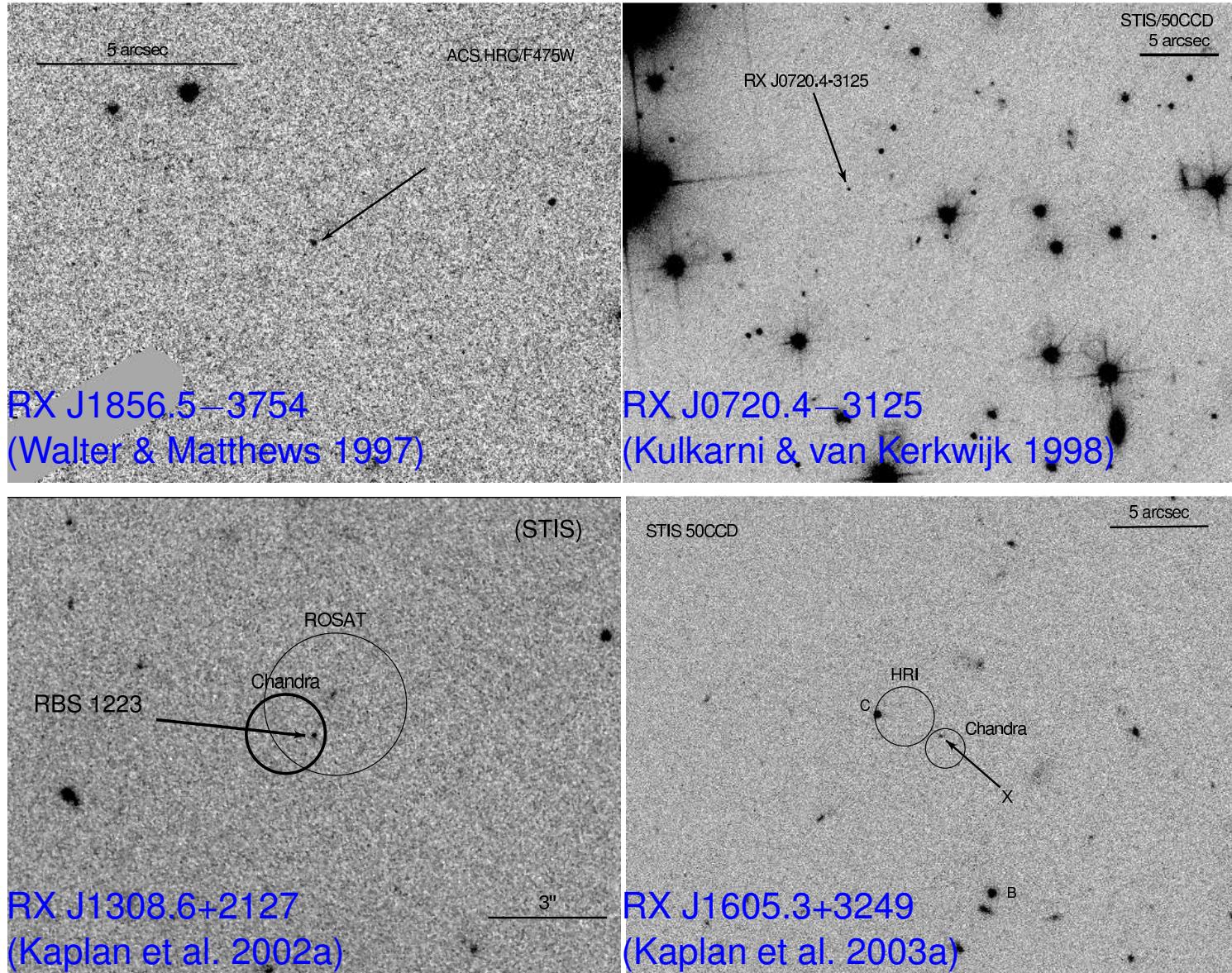
Why study the optical emission:

- Distance:
 - Highest angular resolution possible
 - Enables parallax
- Radius:
 - $F_{\text{opt}} \propto R^2 T$, while $F_{\text{X}} \propto R^2 T^4$
 - X-ray gives T , but optical gives R

The Sample

- *ROSAT* All-Sky Survey, 0.1–2.4 keV (Voges et al. 1996)
- Ideal for 10^5 – 10^6 yr cooling or accreting NSs
- ~ 100 pc: **Geminga**, RX J1856.5–3754
- ~ 300 pc: *PSR B0656+14*, RX J0720.4–3125,
RX J1605.3+3249
- $\gtrsim 500$ pc: *PSR B1055–52*, RX J2143.0+0654,
RX J0806.4–4123, RX J1308.6+2127, RX J0420.0–5022
[italic=radio PSR, red=pulsations]
- ~ 50 more (Rutledge et al. 2003)
⇒ Neutron Star Diversity

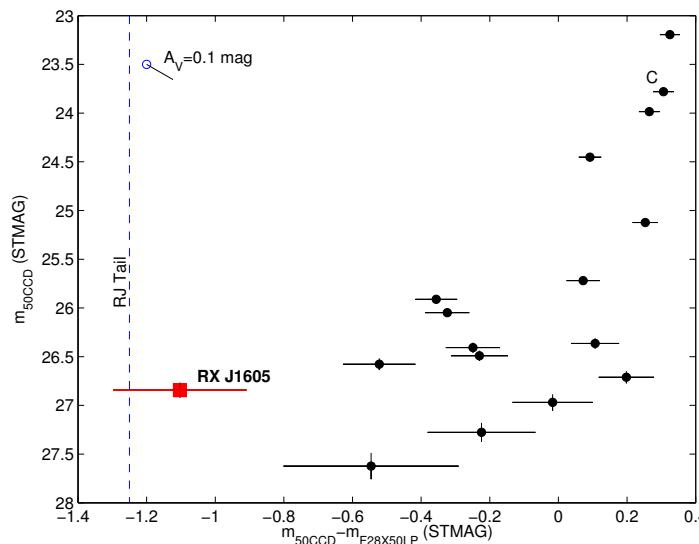
Optical Counterparts



Optical Counterparts

Identification methods:

Source	Position	Colors	Proper Motion
RX J1856.5–3754	Yes	Yes	Yes
RX J0720.4–3125	Yes	Yes	Yes
RX J1605.3+3249	Yes	Yes	...
RX J1308.6+2127	Yes



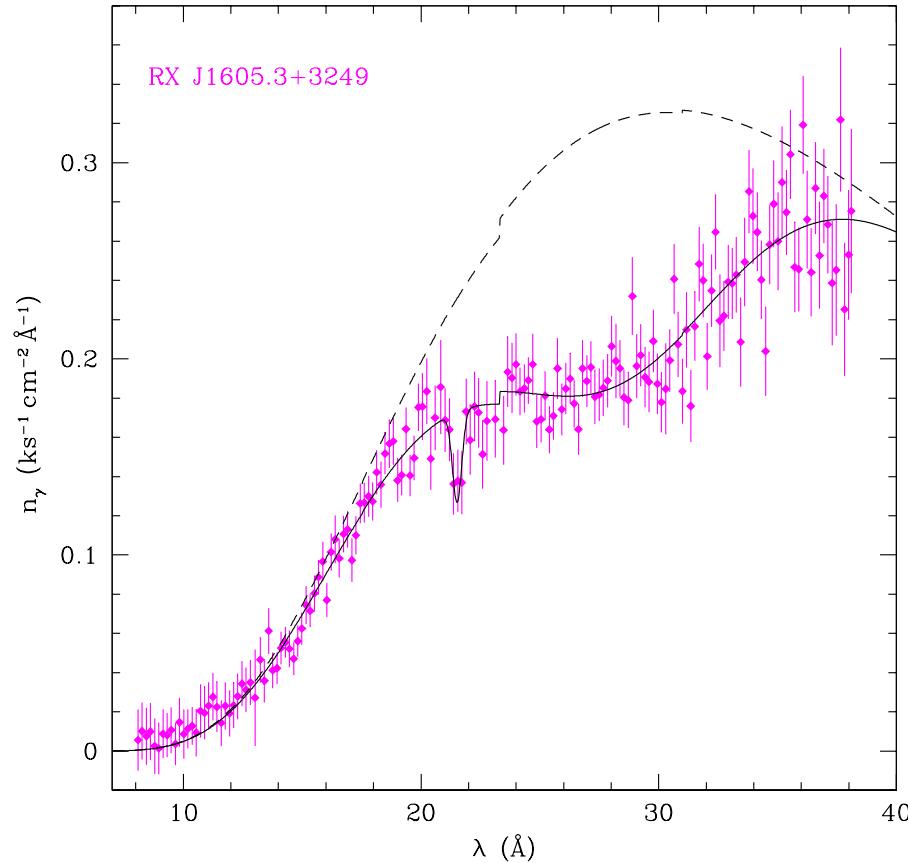
Current Data (X-ray + Optical)

- Thermal sources only (Haberl 2003):

Source	P (sec)	d (pc)	Optical?	X-ray Features?
RX J1856.5–3754	...	180	$V = 25.7$	No
RX J0720.4–3125	8.39	350?	$B = 26.6$	No
RX J1605.3+3249	...	~ 300?	$V \approx 26.8$	0.4 keV
RX J1308.6+2127	10.31	~ 500?	$V \approx 28.6$	0.3 keV
RX J0420.0–5022	22.69	~ 500?	$B > 25.5$...
RX J0806.4–4123	11.37	~ 500?	$B > 24$...
RX J2143.0+0654	...	~ 500?	$R > 23$...

- Nothing perfect
- B from features: 10^{13} – 10^{14} G
- B for RX J0720.4–3125 $\lesssim 3 \times 10^{13}$ G (timing, spectrum)

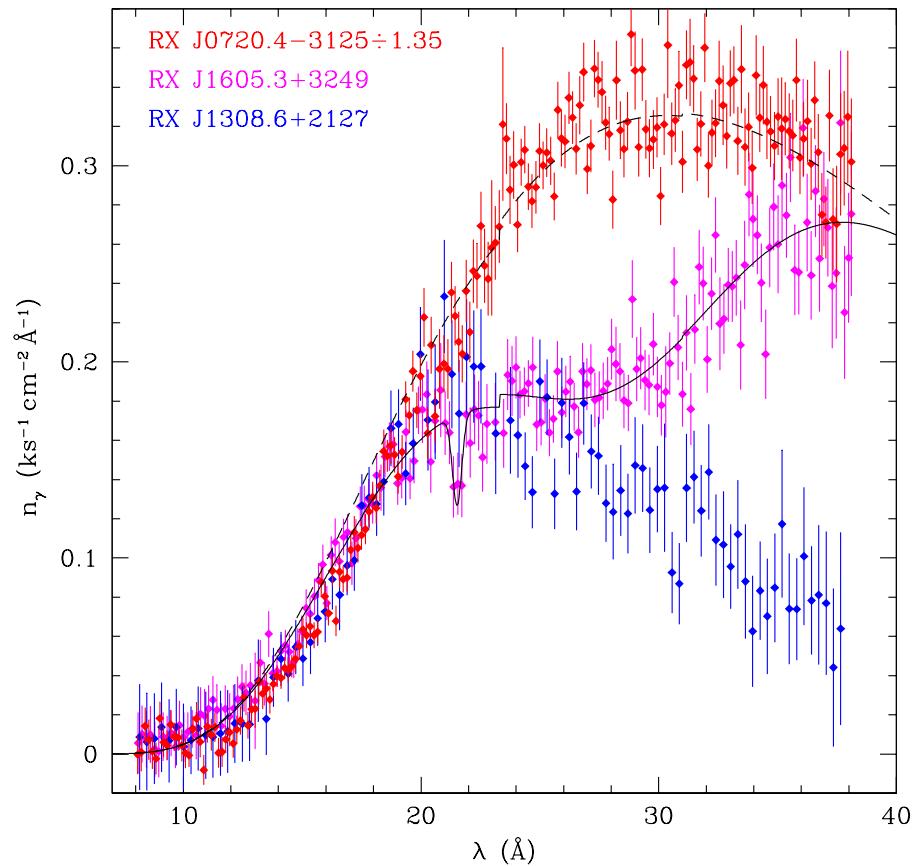
Aside: *XMM* Spectrum of RX J1605



(van Kerkwijk et al. 2003)

- Broad feature at 0.4 keV ($\text{EW} \approx -100 \text{ eV}$)
- Narrow feature at 0.58 keV? ($\text{EW} \approx -1.7 \text{ eV}$) $\rightarrow \text{O VII?}$
- But no pulsations

Aside: *XMM* Spectrum of RX J1605

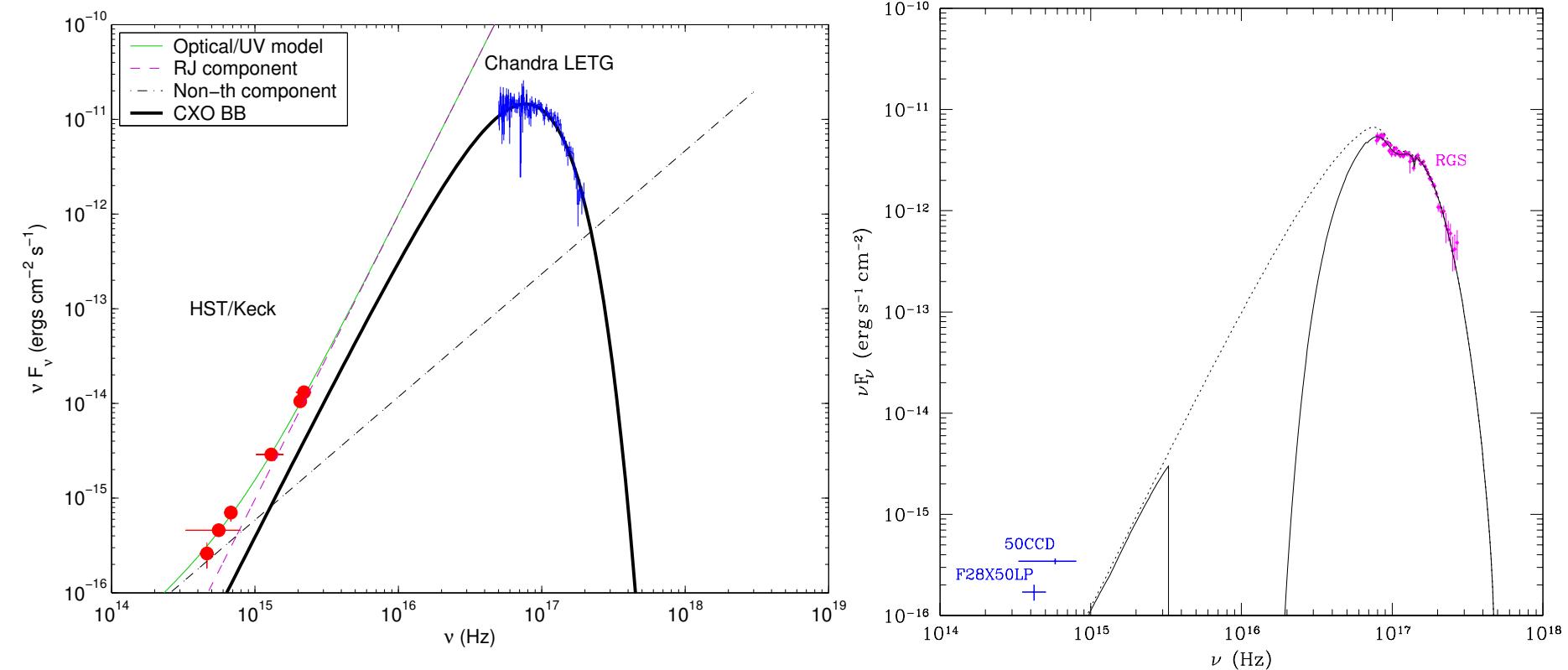


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Optical Excess

- Optical flux is over extrapolation of X-ray blackbody
RX J0720.4–3125 & RX J1605.3+3249:



(Kaplan et al. 2003b; van Kerkwijk et al. 2003)

Optical Excess

- Optical flux is over prediction of X-ray blackbody
- Optical excess is similar among sources

Source	kT (eV)	m_V (mag)	$\log f_X/f_V$	Optical Excess
RX J1856.5–3754	61	25.8	4.4	6
RX J0720.4–3125	81	26.8	4.6	6
RX J1605.3+3249	92	27.1	4.8	9
RX J1308.6+2127	85	28.7	5.0	5

Optical Excess

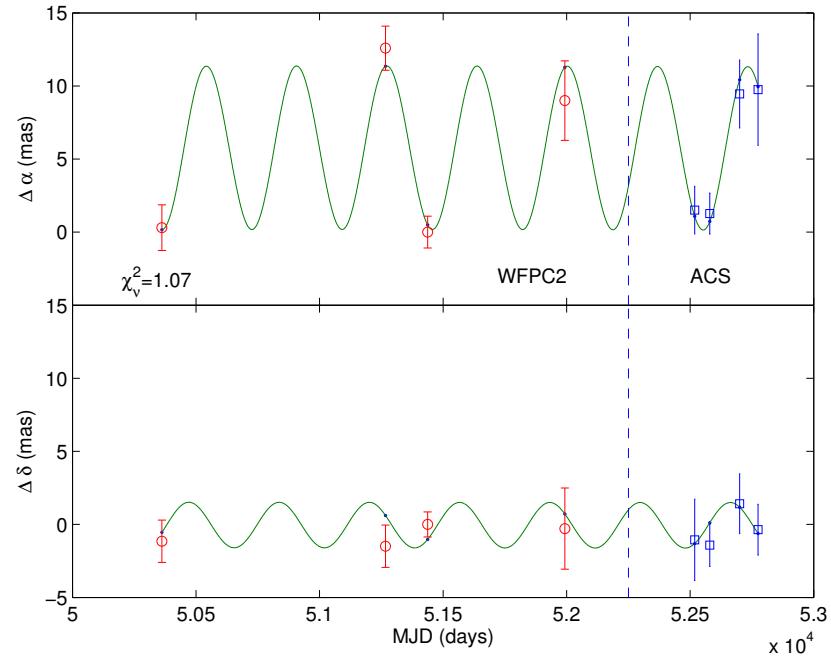
- Can be explained by:
 - 2 blackbody/ T -gradient (e.g., Braje & Romani 2002)
 - ◊ Easy, but unphysical
 - ◊ And why no pulsations in RX J1856.5–3754, RX J1605.3+3249
 - “Thin” atmosphere (e.g., Motch et al. 2003)
 - ◊ H atm. is optically thin to X-rays, so just see BB
 - ◊ But is optically thick to optical photons, so see bigger & cooler RJ-tail
 - ◊ More physical
 - ◊ But still simplified, and must be fine-tuned
 - ◊ Need to account B !

What Are They?

- Do not seem to be magnetars based on \dot{P} (Zane et al. 2002; Kaplan et al. 2002b)
- But may have substantial B (inferred from features) just the same (Haberl et al. 2003)
- Similar to “young” (10^5 yr) low- \dot{E} pulsars?
 - PSR J1814–1744 ($P = 3.98$ s, $B = 5.5 \times 10^{13}$ G, $\dot{E} = 4.7 \times 10^{32}$ ergs s $^{-1}$; Camilo et al. 2000)
 - PSR J1847–0130 ($P = 6.7$ s, $B = 9.4 \times 10^{13}$ G, $\dot{E} = 1.7 \times 10^{32}$ ergs s $^{-1}$; McLaughlin et al. 2003)
- Or like “old” (10^8 yr) pulsars beyond “death-line”?
- Could the INSs be off-beam versions of these PSRs?
- Would imply a substantial population of similar sources

RX J1856.5–3754

- O/UV emission **very** thermal (van Kerkwijk & Kulkarni 2001)
- See H α nebula: constrains \dot{E}
- Distance: $d = 178^{+22}_{-17}$ pc
- Implies large BB radius $R_\infty \approx 20$ km



(H α credit: ESO/M. H. van Kerkwijk)

Parallax of RX J1856.5–3754

- Connected 4 epochs of *HST/WFPC2* with 4 epochs of *HST/ACS* (very consistent, $\chi^2_\nu = 1.07$)
- Using effective-PSF technique to get full information on sub-pixel scales (Anderson & King 2000)
- Allowed for:
 - Changing plate-scale
 - Changing rotation
 - Proper motion of background stars
- 1–2 mas precision (in position of NS) at each epoch
- ACS data will improve as distortion maps/fitting algorithm are refined
- Analysis is continuing, with 4 more epochs coming

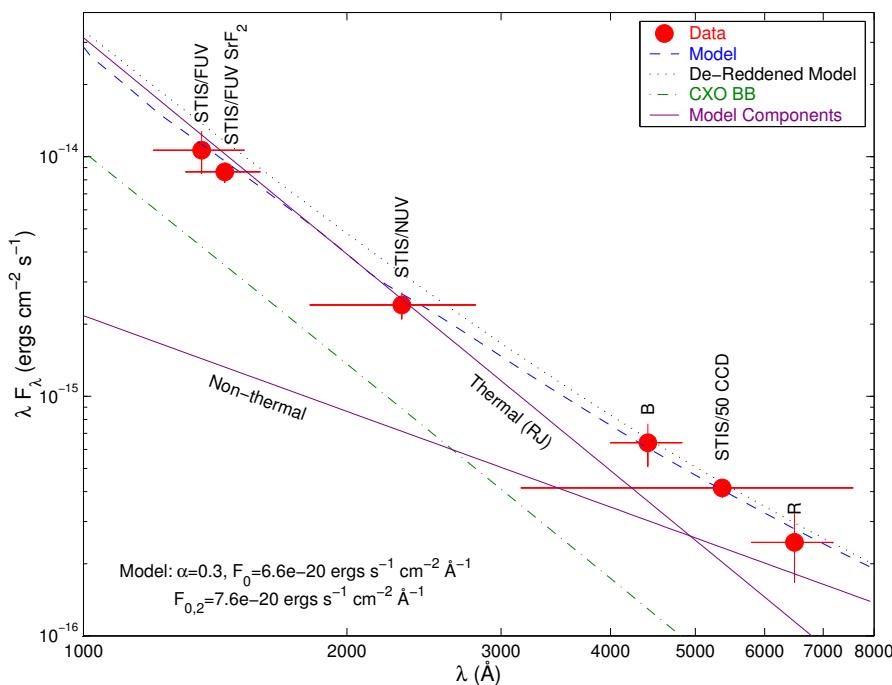
Parallax of RX J1856.5–3754

Instrument	Epochs	Parallax	Distance	Ref.
WFPC2	3	16.5 ± 2.3	61 ± 9	(Walter 2001)
WFPC2	3	7 ± 2	140 ± 40	Kaplan et al. (2002c)
WFPC2	4	8.5 ± 0.9	117 ± 12	Walter & Lattimer (2002)
WFPC2	4	6.0 ± 1.2	167 ± 33	this work
WFPC2+ACS	8	5.6 ± 0.6	178 ± 20	this work

- Same result if:
 - Remove 1 epoch
 - Fit for fewer transformation parameters
 - Change convergence criteria

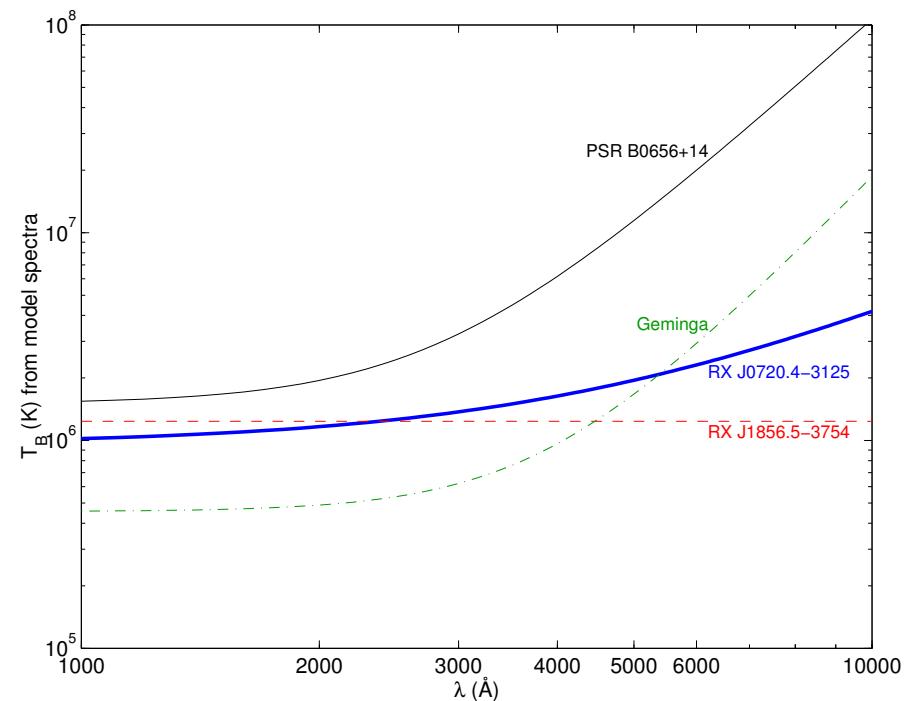
RX J0720.4–3125

- Some non-thermal optical emission (Kaplan et al. 2003b)
 - Like PSRs



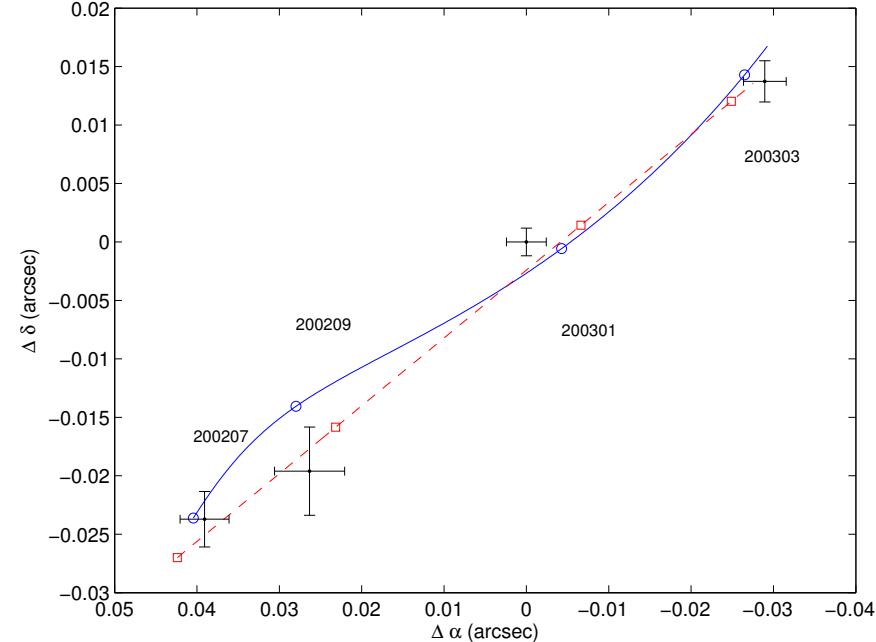
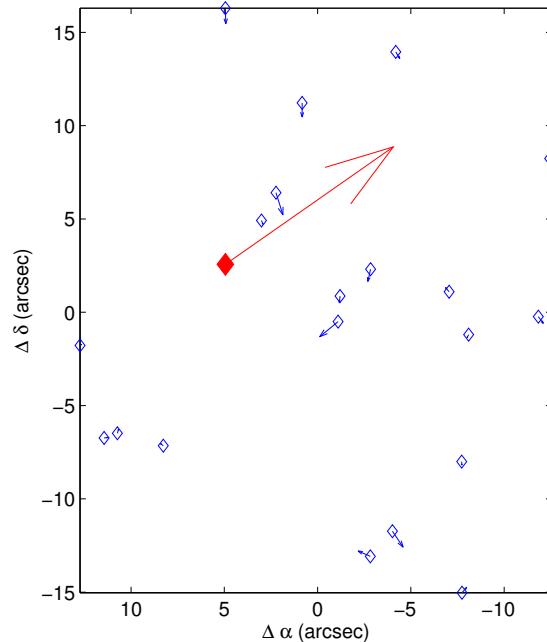
$$T_B = \frac{F_\nu \lambda^2 \Omega}{2k}$$

$$R = 10 \text{ km}$$



RX J0720.4–3125

- Some non-thermal optical emission (Kaplan et al. 2003b)
- Proper motion: 100 mas/yr, 200 km/s (Motch et al. 2003)
- *HST* data improves accuracy (factor of 2 w/ 4 epochs)
- Parallax
 - Low significance now ($\approx 1\sigma$)
 - But should improve (better analysis, 4 more epochs)

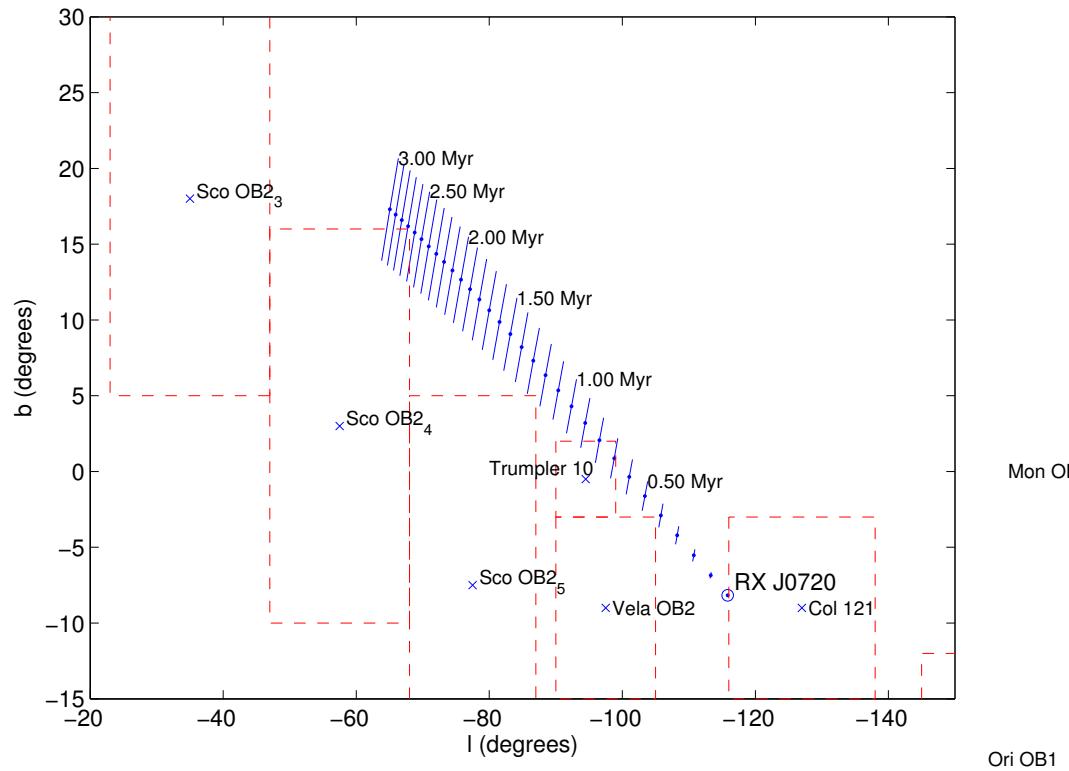


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- Parallax
 - Low significance now ($\approx 1\sigma$)
 - But should improve (better analysis, 4 more epochs)
- Cannot do absolute photometry yet (ACS photometry not calibrated)
- But see no variability over 4 epochs (total span: 9 months)

RX J0720.4–3125

Origin:



- Best association (de Zeeuw et al. 1999): Trumpler 10
 - Age would be $\approx 6 \times 10^5$ yrs — consistent with cooling
- Or could others (e.g., Sco OB2₄ at $\approx 3 \times 10^6$ yrs)

Future

- 4 more epochs of *HST* data for RX J1856.5–3754, RX J0720.4–3125
 - Better analysis \Rightarrow higher precision parallaxes
 - Goals:
 - ◊ 5% parallax for RX J1856.5–3754
 - ◊ 20–30% for RX J0720.4–3125
- Searches for H α nebulae
 - Constrain \dot{E}
 - Especially useful if v known
- *Chandra/XMM* observations of more sources
 - Position (\Rightarrow more optical counterparts)
- Additional parallaxes (Geminga, RX J1605.3+3249)?
- Optical pulsations?
 - Would help with surface models

Conclusions

- Optical/UV offers unique window to constrain INSSs:
 - Spectral energy distribution
 - Distance
 - Velocity
 - Origin/age
 - \dot{E}all of which help determine EOS
- INSSs are very faint — require 8–10 m telescopes or *HST*
- Will big telescopes of the future (CELT, OWL, etc.) make this more routine?